Scattering and Flare of 10x Projection Cameras for EUV Lithography

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INTRODUCTION

Scattering becomes increasingly important as the wavelength of light is reduced. For a reflective optic the total integrated scatter increases roughly as $1/\lambda^2$. The detrimental effects of scattering are: 1) a reduction in throughput due to light being lost from the camera; 2) a reduction in the image contrast by light which is redirected from bright regions of the imaged pattern into otherwise dark regions. A loss in throughput may be compensated, for example by increased exposure time. However, a reduction in the contrast degrades the image quality and is a more serious problem. The level of the scattered light in an otherwise dark region we refer to as flare. Flare reduces the exposure latitude. In addition, flare may cause the contrast to vary over the field of view if the pattern density varies, or as the edge of the field is approached. In turn, a variation in contrast will result in a variation in the printed line width.

Optical substrates for two Schwarzschild cameras have been fabricated with extremely strict tolerances on both figure and finish errors. These cameras are representative of the current state-of-the-art in optical fabrication. The substrates were coated and assembled into cameras. The characterization of the scattering from the individual mirrors is described here along with the determination of the flare level in the assembled cameras.

THEORY

The scattering from a multilayer can be rather complex; however, for small scattering angles the multilayer may be regarded as a single reflecting surface. This approximation is valid for the small angles corresponding to the field of view (0.1 deg) of the Schwarzschild camera being discussed here. The scattering from a single surface may be calculated according to[1]

$$\frac{1}{I_0}\frac{dI}{d\Omega} = \frac{16\pi^2}{\lambda^4} R \cdot S \cdot \mathrm{PSD}(f) \qquad (1)$$

where R is the reflectivity of the smooth surface and $S = \exp[-(4\pi\sigma/\lambda)^2]$ is the Strehl ratio. The two dimensional power spectral density (PSD) describes the surface roughness, which is assumed to be isotropic and is a function of the radial spatial frequency, $f = \sin\theta/\lambda$, where θ is the scattering angle measured from the specularly reflected beam. This expression assumes that the incident and scattered angles are small (close to the normal) and the scattering is rotationally symmetric about the reflected beam.

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The effect of scattering on the image produced by a camera may be described by a scattering point spread function (PSF_{sc}). The image is calculated by convolving the PSF with the aerial image intensity calculated without scattering, but including the effects of the figure errors of the optics and the coherence of the illumination. For a single mirror, the PSF_{sc} is proportional to the angular distribution of scattering,

$$\mathrm{PSF}_{\mathrm{sc}}(r) = \frac{1}{\rho^2}\frac{1}{I_0 R}\frac{dI}{d\Omega} \qquad (2)$$

where ρ is the distance between the mirror surface and the image plane.

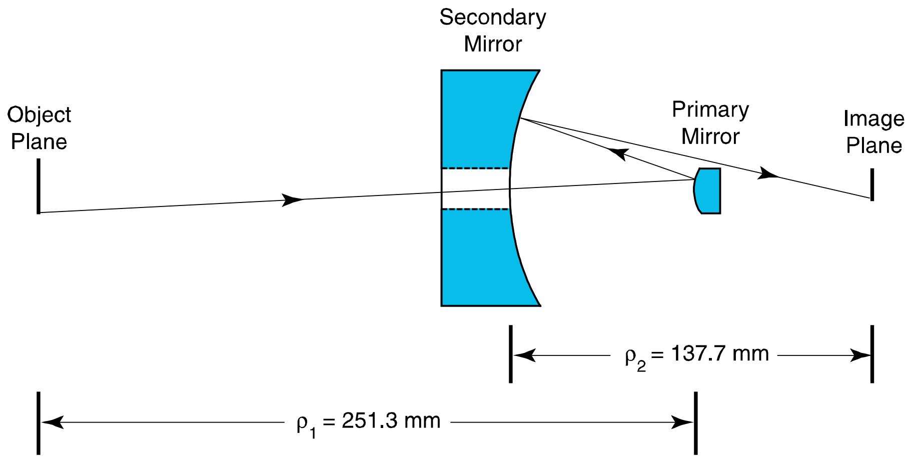

Figure 1. The 10x Schwarzschild camera.

For the Schwarzschild 10x camera consisting of two mirrors, shown in Fig. 1, the scattering point spread function is given by[2]

$$\mathrm{PSF}_{sc}(r) = S\delta(r) + \frac{16\pi^2 S}{\lambda^4 \rho_2^2}\left(\mathrm{PSD}_2\left(\frac{r}{\lambda\rho_2}\right) + \alpha^2 \mathrm{PSD}_1\left(\frac{\alpha r}{\lambda\rho_2}\right)\right) \quad (3)$$

where the delta function which accounts for the specular image has been explicitly included. The first term with the brackets describes the scattering from the secondary (final) mirror with PSD_2 at a spatial frequency of $f = r/\lambda\rho_2$. The distance from the secondary mirror to the image plane is ρ_2 = 137.7 mm. The second term describes the scattering from the primary mirror at a spatial frequency which is scaled by $\alpha = M\rho_2/\rho_1 = 5.48$ relative to that of the secondary, where M = 10 is the camera magnification and ρ_1 = 251.3 mm is the object to primary mirror distance.

The reduction of image contrast by scattering may be seen by considering the intensity in an isolated dark line within a bright field. The aerial image intensity may be calculated by convolving the image produced in the absence of scattering with the PSF given above. The intensity in the center of the line is increased due to the tail of the PSF which extends from the bright regions of the field into the dark line. As the width of the line is reduced the intensity in the center of the line increases because of the contribution from nearby bright points. Since it is convenient to describe the effects of scattering on the image contrast by a single number, *flare* is often defined as the intensity in the center of a dark line of a specified width in a uniformly bright field.

SCATTERING FROM THE INDIVIDUAL MIRRORS

EUV scattering was measured for each of the two secondary mirrors after they were multilayer coated. The measurements were performed at the reflectometry and scattering beamline (6.3.2) operated by the Center for X-ray Optics at the Advanced Light Source (ALS) in Berkeley. EUV synchrotron light, at a wavelength of 13.4 nm, was used to illuminate a pinhole at a distance of 110 mm from the mirror. The pinhole was re-imaged with a magnification of unity into a channeltron detector which could be scanned in angle. The angular distribution of scattering for the S2 mirror is shown in Fig. 2. The calculated angular distribution is also shown and was obtained from Eq. (1) and the measured PSDs of the coated surfaces. The single surface scattering approximation is not expected to hold for large angles and indeed the calculated curves deviate from the measurements above about 15 deg.

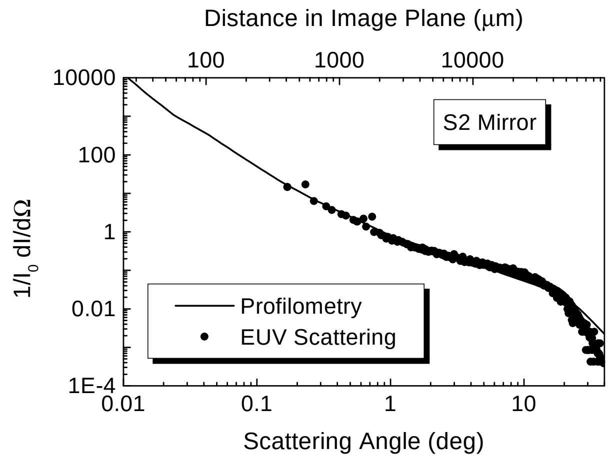

Figure 2. EUV scattering from the secondary mirrors. The solid lines are the calculated scattering for a single surface with the PSD measured for the top (coated) surface of each of the mirrors.

FLARE OF THE CAMERA

The mirrors were assembled into cameras and aligned. The flare of the assembled camera 1 (consisting of the P3 and S2 mirrors) was determined in three different ways. In the first test the camera was used to image a 750-nm pinhole which was illuminated with synchrotron light at the EUV Interferometry beamline (12.0) at the ALS. The light passing through a 0.5-mm square aperture in the image plane was detected with a photodiode. The size of the aperture was chosen to match the field of view of the camera. With the aperture centered on the image of the pinhole, the intensity of light measured by the photodiode is the sum of the specular and scattered light. The amount of light contained in the specular image can be determined by using the edge of the aperture as a knife-edge to scan through the image of the pinhole. The results of such a scan are shown in Fig. 3 where the photodiode signal was normalized to that obtained when the aperture was centered on the image. The flare can be directly obtained from the measured scan. Choosing to specify the flare for a 4 micron line, the width of the scan in Fig. 3, the measured flare is 4.5%. This is in good

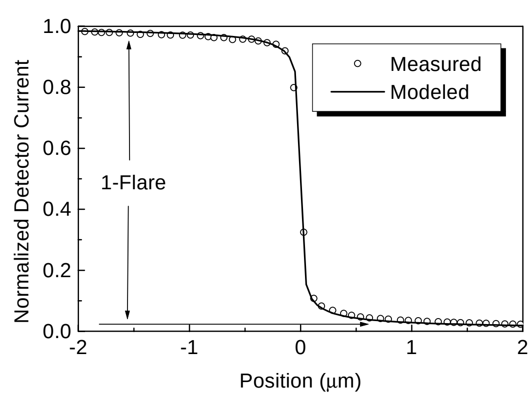

Figure 3. Knife-edge scan through the image of a 750 nm pinhole produced with camera 1. The flare is the amount of light scattered outside the image. For a 4 micron line, the width of the scan, the flare level is 4.5%. The solid line was calculated from the surface profile measurements on the individual optics of camera 1.

agreement with calculations based on the measured surface roughness of the individual optics, shown as a solid line in Fig. 3, which would predict a flare of 4% for a 4-micron line.

Two additional independent measurements have been performed which also put the flare level in the 4-5% range. One uses the wavefront errors determined by EUV interferometry[3] to determine the point spread function (PSF) of the camera. The wings of the PSF, which describe the level of scattering, are determined from the high frequency wavefront errors. The PSF obtained from the Fourier transform of the measured wavefront, both phase and amplitude, is shown in Fig. 4. Finally, the flare was measured lithographically with camera 1 installed in the Sandia 10xI system. In this measurement, 4 micron lines were printed and it was found that an overexposure of 20x did not quite clear the line. This puts the flare level at somewhat less than 5%.

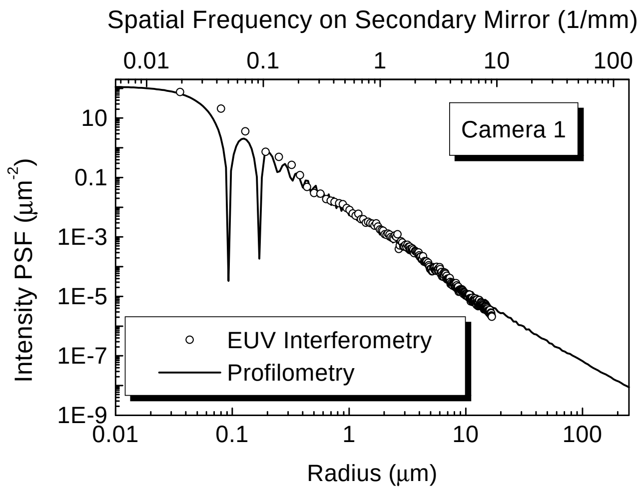

Figure 4. The Point Spread Function of camera 1 as measured by EUV interferometry is compared to that calculated from Equation (3) and the measured PSDs of the individual mirrors.

CONCLUSIONS

The relationship between the optical finish of the mirror substrates and the flare of an assembled EUV camera is clearly demonstrated. The improvements made in mirror finishing translate directly into a reduced level of flare compared with previous cameras[4]. These results are very encouraging for the success of the next generation of EUV imaging optics which will have more mirrors and an increased field of view, both of which tend to increase the level of flare.

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